# RESEARCH NOTES
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# Sensitivity of Bridge Cost to Design Earthquake Loading


***RESULTS: The Caltrans PEER-Lifelines Partnership recently investigated how highway bridge costs are affected by designing to varying levels of seismic loading. The study found that for typical highway bridges, ground motion stemming from smaller magnitude events ($M_w$=6.5) had little effect on costs up to PGA values of about 0.7 g. For the case of larger magnitude events ($M_w$ = 7.25 and 8.0) costs increased an average of about 7% for every 0.1g increase in PGA beyond about 0.45g. These results provide unique data that can be used by Caltrans to develop a more refined seismic risk management strategy.***


**Why We Pursued This Research**

Selecting an appropriate level of seismic loading for the design of bridges can be a complicated decision with many considerations. Key factors include the degree of lost functionality with increasing levels of shaking, the bridge's ultimate resistance to collapse, and the likelihood for strong shaking to occur. All of these factors are active areas of research.

Also important are economic issues. Although designing for higher levels of loading improves seismic performance, at some point a design level is reached where the added engineering and societal benefit of designing to an even higher standard is no longer worth the additional cost. To define this point, one must be able to relate seismic performance to cost. There has been substantial recent research relating bridge performance to seismic demand, but little information was available regarding the cost impact of designing to different levels of seismic demand. This project aimed to provide that much needed cost data.

**What We Did**

The PEER-Lifelines Program contracted with OPAC Engineers of San Francisco to investigate the cost sensitivity of typical highway bridges to varying levels of seismic loading. OPAC devised a novel strategy that allowed a large number of "cost points" to be developed with reduced design effort.

Seven bridge configurations were ultimately considered, as shown in Table 1. Since a high proportion of Caltrans' bridges are cast-in-place (CIP) post-tensioned (P/S) box girder type, all but one model was based on this construction. One model (No. 6) used precast I-girders. Span lengths varied from 100 to 150 feet and both single and multicolumn configurations were considered. All models assumed a 22 foot column height except for Model No. 11 which had a 50 foot column height. Possible influences of alignment curvature and skew were investigated in Model Nos. 9 and 10, respectively. All other bridge models maintained a straight geometry.

*Methodology*

OPAC's approach was to design multiple versions of each bridge configuration, with each version using different column size and/or percentage of steel. Each version was designed with a balanced set of properties but without regard to seismic demand. For each model version, numerous response spectrum analyses were performed using multiple scalings (PGA values) of the spectral shapes associated with soil profile Type D, $M_w$

| | | | | | | $M_w$=6.5 | | $M_w$=7.25 & 8.0 | |
|---|---|---|---|---|---|---|---|---|---|
| Model No. | Structure Type | Span (ft) | Width (ft) | No. Col | Special Feature | Cost Sensitivity* | Threshold PGA (g)** | Cost Sensitivity* | Threshold PGA (g)** |
| 1 | CIP P/S Box | 150 | 39 | 1 | | 14% | 0.79 | 13% | 0.47 |
| 3 | CIP P/S Box | 100 | 39 | 1 | | 2% | --- | 8% | 0.40 |
| 4 | CIP P/S Box | 100 | 68 | 3 | | 2% | 0.69 | 6% | 0.49 |
| 6 | PC/PS I Gird. | 100 | 68 | 3 | | 4% | 0.64 | 6% | 0.46 |
| 9 | CIP P/S Box | 150 | 27 | 1 | 1000' rad. curve | 0% | 1.0 | 17% | 0.57 |
| 10 | CIP P/S Box | 100 | 68 | 3 | 30 deg. skew | 2% | 0.68 | 8% | 0.47 |
| 11 | CIP P/S Box | 150 | 39 | 1 | 50' tall column | 0% | 1.0 | 29% | 0.67 |

Table 1: Model descriptions and cost sensitivity results

*Cost Sensitivity is defined as the percentage cost increase ($\$/ft^2$) for an increase of 0.10 g in PGA.
**Threshold PGA is defined as the PGA level below which Cost Sensitivity is approximately zero.

6.5, 7.25, and 8.0 spectral response curves as provided in Appendix B of the Caltrans Seismic Design Criteria (SDC). These analyses allowed OPAC to relate the column displacement demand for each model to a scale factor (or PGA) for each of the three spectral shapes (magnitudes) considered.

Column displacement capacity was calculated for each model using moment-curvature analysis and static push-over analysis per SDC. Critical scale factors (PGA values) were then determined for each model and magnitude spectral shape by equating demand with capacity.

Finally, Caltrans construction cost data was utilized to estimate the cost of each bridge model. This cost data was then plotted as a function of critical scale factor (PGA). Figure 1 provides an example for Model No. 1.

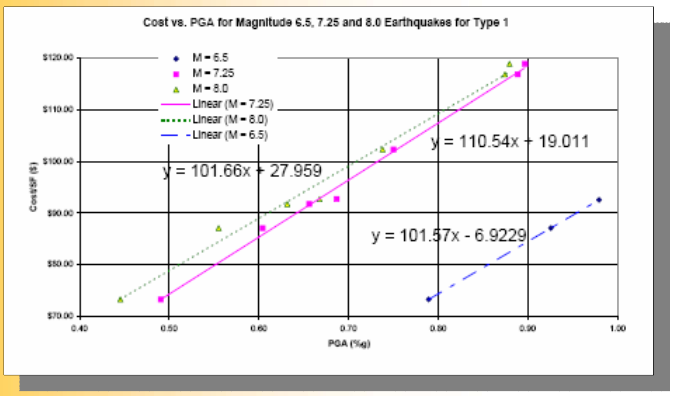


Figure 1: Model 1 cost variability for 3 EQ magnitudes

*Foundations*

Bridge foundations represent a sizable component of overall bridge cost and an important component of potential cost increase. In light of the large diversity of foundation types and soil conditions encountered in California, a unique strategy was required to capture their cost contribution while not biasing the results due to over-reliance on one foundation type or site condition. A review of construction cost data led the investigators to consider four foundation types: drilled shafts and driven H-piles, precast concrete piles, and steel pipe piles. By developing representative soil profiles and selecting typical pile sizes for each foundation type, design charts were developed that enabled rapid determination of appropriate foundation size for given levels of loading.

These charts were then used to design four foundations (one for each pile type) for each bridge model. The cost of the foundation component for a given model was then calculated as a weighted average of these four foundations, with the weighting being determined by the relative use of each foundation in California.

It should be noted that only relatively competent soil conditions were considered. Bridge cost sensitivity at soft soil locations would likely be higher than that reported in this study.

**Research Results**

Cost sensitivity data for each model is presented in Table 1. The following observations are noted:

- Bridge cost is relatively insensitive to design ground motion level for $M_w$ 6.5 earthquakes (and smaller). These earthquakes have significantly less energy at typical bridge periods than larger magnitude earthquakes resulting in much lower displacement demands.
- Bridges with single column bents appear to be more cost sensitive than those with multicolumn bents.
- Bridges with longer span lengths (e.g. 150ft.) are more cost sensitive than those with shorter span lengths.
- Use of precast I-girders had little affect on cost sensitivity.
- Curved alignments may be more cost sensitive than straight alignments.
- Skewed geometries may have a small affect on cost sensitivity.
- Column height appears to have a large effect on cost sensitivity, but only at higher threshold PGA's.

It should also be recognized that the results provided in Table 1 were developed only for Type D (stiff soil) response spectrum shapes. Type D sites are overwhelmingly the most common for Caltrans bridge design. Type B and C sites (soft rock and very dense soil) do exist, however, and their reduced spectral energy at longer periods would likely result in somewhat lower cost sensitivities and higher PGA thresholds.

**Recommendations**

For regions where the seismic hazard is dominated by the potential for smaller magnitude events, a cost sensitivity of 2% for every 0.1g increase above 0.70g PGA appears to be justified. In regions dominated by the potential for higher magnitude events, a cost sensitivity of 7% for every 0.1g increase above 0.45g PGA is appropriate.

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